GCM simulations of the atmospheric coupling between the Venusian lower atmosphere and thermosphere through atmospheric waves

著者	星野 直哉
number	55
学位授与機関	Tohoku University
学位授与番号	理博第2691号
URL	http://hdl.handle.net/10097/56856

氏名・(本籍)	星野直哉(ほしのなおや)
学位の種類	博　士(理　学)
学位記番号	理博第２６９１号
学位授与年月日	平成24年３月27日
学位授与の要件	学位規則第４条第１項該当
研究科，専攻	東北大学大学院理学研究科（博士課程）地球物理学専攻
学位論文題目	GCM simulations of the atmospheric coupling between the Venusian lower atmosphere and thermosphere through atmospheric waves (大気波動を介した金星熱圏-下層大気結合の数値シミュレーション)
論文審査委員	（主査）准教授　寺田直樹
	教授　笠羽康正
	教授　藤原　均（成蹊大学）
	教授　岡野章一
	准教授　村田　功（環境科学研究科）

論文目次

論 文 内 容 要 旨

Abstract

In this study, we have performed simulations considering the planetary-scale waves and gravity waves in order to investigate the three subjects related to atmospheric coupling between the Venusian lower atmosphere and thermosphere through atmospheric waves: 1) basic features of the mesospheric and thermospheric general circulation, 2) effects of planetary-scale waves (thermal tides, Rossby wave and Kelvin wave) on the mesospheric and thermospheric winds and the temporal variation of the O_2-1.27 μm nightglow at about 95 km, and 3) effects of gravity waves on the driving of the retrograde zonal wind (RZW) as fast as about 100 m/s observed in the 95-110 km region.

We have developed a new general circulation model (GCM) which covers the altitude region between 80 km and the exobase (about 180 km). The spatial resolutions are 5.6°× 5.6° in longitude and latitude, and 0.5 scale height in altitude. The GCM calculates temperature, wind velocity, and number density (O, CO and CO_2) distributions by solving primitive equations. We consider the eddy and molecular diffusions, viscosity, and heat conduction in our GCM. We have also developed a 1-D O_2-1.27 μm nightglow model. The horizontal nightglow distribution can be obtained by using the nightglow model and 3-D composition distribution calculated in our GCM.

First, we have performed simulations without the consideration of the planetary-scale waves in order to understand the basic features of the Venusian mesosphere (70-110 km) and thermosphere (>110 km). In the calculations, the momentum transport effects by gravity waves have been considered with the parameterization (Rayleigh friction) used in Bougher et al. (1988). The GCM simulations have been performed for the solar maximum ($F_{10.7}$=206 at the Earth) condition with the wind velocity of 0 m/s at the lower boundary. The Subsolar-to-Antisolar (SSAS) wind with the maximum wind velocity of about 250 m/s is driven above about 90 km by the pressure gradient force between the dayside and nightside.

We have investigated the dependence of the mesospheric wind velocity on the superrotation strength by GCM simulations considering the superrotation at the lower boundary. We have assumed the solid body rotation with the equatorial wind velocities of about -20, -40, -60, -80 and -100 m/s (hereafter LB20, LB40, LB60, LB80 and LB100 conditions) as the superrotation wind at the lower boundary. The meridional wind velocity has been set to be 0 m/s at the lower boundary. In our simulations, the superrotation given at the lower boundary decays with height rapidly in all conditions. The strength of the superrotation becomes almost 0 m/s above about 90 km in the LB100 condition. The simulation results suggest that the Rayleigh friction mainly contributes to the decay of the superrotation.

Secondary, we have performed simulations with the consideration of the planetary-scale waves without the superrotation in the solar maximum condition. The planetary-scale waves are imposed by moving the geopotential fluctuations, which correspond to the wave structures, at the lower boundary. The amplitudes of the waves at the lower boundary are determined based on the study by Rossow et al. (1990) and the linear wave theory. The thermal tides, Rossby wave and Kelvin wave rotate around Venus with periods of 117 days, 5 days and 4 days, respectively. The diurnal and semi-diurnal tides propagate up to the exobase with the maximum values of about 0.6 m/s and 1.2 m/s, respectively, at the exobase. However, the wind velocity fluctuation is too small to affect the background wind. The zonal wind fluctuation caused by the Rossby wave

increases with height in the 80-103 km region with the maximum value of about 0.4 m/s, which is negligible small compared with the background wind, at about 103 km. The Kelvin wave causes the zonal wind fluctuation with the maximum amplitude of about 6.0 m/s at about 103 km. The Kelvin wave, which transports the westward momentum upward, causes the westward atmospheric acceleration of about 3.5 m/s at about 105 km. However, the westward acceleration caused by the Kelvin wave cannot reproduce the observed RZW strength. On the other hand, this calculation suggests that the Kelvin wave would cause the temporal variation of the nightglow emission region (23:48LT-00:12LT) and intensity (1.48 MR-1.73 MR) with the period of 4 days.

We have investigated the dependence of the propagation of the Kelvin wave on the strength of the superrotation. We have performed simulations with the Kelvin wave and superrotation wind at the lower boundary for the LB20 ~ LB100 conditions. In cases with the superrotation wind at the lower boundary, the wind fluctuations caused by the Kelvin wave are generally smaller than those without the superrotation wind except for the LB80 condition. The vertical wavelength of the Kelvin wave in the LB100 condition is about 3-4 km at about 85 km while those in the other conditions are about 30 km. These results are consistent with the linear wave theory, which suggests that the wave with the smaller intrinsic phase speed has the smaller vertical group velocity and the smaller wavelength.

Finally, we have investigated effects of gravity waves on the mesospheric and thermospheric winds with the new gravity wave parameterization developed by Medvedev and Klaassen (2000) (MK scheme) instead of Rayleigh friction. The MK scheme can treat the non-linear interaction between gravity waves and the wave damping process caused by the molecular viscosity which were not considered in previous parameterizations. We have performed simulations with the MK scheme in the LB0 and LB40 conditions. In the LB0 and LB40 conditions, the gravity waves with the mean phase speed of about 0 m/s and -40 m/s are imposed at the lower boundary, respectively, since we assume that gravity waves are generated by the shear instability at about 80 km. The simulations have been performed in the solar maximum condition. In the LB0 condition, the SSAS wind with the maximum wind velocity of about 240 m/s is driven at the 06:00LT at the exobase. The wave drag force caused by gravity waves decelerates the SSAS wind. The attenuation of gravity waves is seen above about 145 km because of the wave damping by the molecular viscosity. In the LB40 condition, gravity waves transport the westward momentum upward and drive the RZW with the maximum strength of about -120 m/s at about 125 km. The velocity of the RZW is faster than the mean phase speed of gravity waves (-40 m/s) above about 110 km because of the selective filtering of the eastward propagating gravity waves near the lower boundary. The RZW causes the shift of the O_2-1.27 μm nightglow emission region from 00:00LT to 03:30LT.

We have analyzed the simulated wind velocity distribution in the 95-110 km region where wind velocity has been estimated from the observations of CO and CO_2 lines. This analysis suggests that the dayside wind observation with the CO_2-10 μm lines is suitable for the estimation of the SSAS strength since the SSAS is dominant in the dayside despite of the existence of the RZW. On the other hand, the RZW velocity in about 95-110 km can be obtained from the CO millimeter/sub-millimeter observations by calculating the half of the zonal-mean zonal wind velocity in the nightside since the westward acceleration by gravity waves, which drive the RZW, occurs mainly in the nightside. The day-night difference of the general circulation is consistent with the suggestion from previous observation results (Clancy et al., 2012a).

In this thesis, we suggest the importance of the Kelvin wave on the temporal variation of the thermospheric wind velocity and the nightglow distribution for the first time. In addition, the simulation with the new gravity wave parameterization reveals the detail wind velocity distribution in the 95-110 km region, which is useful to derive the strengths of the SSAS wind and RZW from observations. These simulation results would contribute to the planning of the future ground-based observations and spacecraft missions which aim to investigate the mesospheric and thermospheric general circulation.

論文審査の結果の要旨

金星探査機の大気光観測や地上からの風速観測によって、金星熱圏において約100m/sに達する高速の東西風や激しい風速の時間変動が存在することが指摘されてきた。しかしそれらを駆動すると考えられる下層大気から熱圏への大気波動の伝播の定量的評価は行われておらず、運動量輸送を担う大気波動の種類とその運動量輸送の定量的理解は未解決の課題であった。本論文は、金星の大気大循環モデル (GCM) を用いた数値実験を行い、金星下層大気と熱圏の上下結合を担う大気波動の種類とその運動量輸送を定量的に明らかにすることを目的としたものである。特に、熱潮汐波、ケルビン波、ロスビー波などの惑星スケールの波が熱圏風速場に及ぼす影響、下部熱圏高度でのO2の大気光発光位置の時空間変動に果たす役割、及び、重力波が下部熱圏高度で約100m/sに達する高速東西風の駆動に果たす役割を明らかにすることを主な目的とする。本論文では、これらの目的を達成するために、金星中間圏-熱圏 GCM 及び O2-1.27 μm 大気光化学モデルを新たに開発し、またそれらを駆使して様々な条件下における数値実験を実行し、金星下層大気と熱圏の上下結合過程の解明に寄与する以下の先駆的な成果を挙げた。

1. 下層大気から伝播する惑星スケールの大気波動が、熱圏の風速場に及ぼす影響を明らかにする為に、下端条件に熱潮汐波、ケルビン波、ロスビー波を強制的に与えた数値実験を実行し、その結果、惑星スケールの大気波動の中でも4日周期をもつケルビン波の寄与が卓越することを明らかにした。下層大気から伝播したケルビン波は下部熱圏高度で約±5m/sの風速変動を引き起こし、O2の大気光分布に23:48-00:12LTの位置変動と1.48-1.73MRの輝度変動を引き起こすことを定量的に示した。そして、観測データとの比較検討を行い、ケルビン波による運動量輸送が、観測で示唆される風速と大気光の時空間変動の一部を定量的に説明することを示した。しかしながら、ケルビン波による運動量輸送では、約100m/sに達する高速東西風を駆動するには不十分であり、重力波などの他の大気波動による運動量輸送が重要となる可能性を示唆した。
2. 分子粘性による波の減衰を考慮した新しい重力波パラメタリゼーションを適用することによって、下層大気からの重力波の伝播によって駆動される中間圏-熱圏高度での風速の詳細分布を明らかにした。下端条件として、スーパーローテーションを模擬した風速を与え、またその値を様々に変化させた数値実験を行うことによって、背景風による重力波の選択的フィルタリング効果により、高度80kmにおける波の平均位相速度より速い高速東西風を熱圏高度で形成可能であることを示した。そして、高度80km付近でシアー不安定により発生する重力波は、高度90km以上で高速東西風を形成しうることを明らかにした。この高速東西風は、O2の大気光分布を00:00LTから03:30LTに移動しうることを明らかにした。また、高度95-110kmにおける高速東西風と昼夜間対流の分布を定量的に評価し、高速東西風と昼夜間対流の寄与を切り分ける観測の実現に有用なデータを示した。

本論文は、従来の研究で行われていた熱圏GCMの計算を、中間圏高度まで拡張して実行することにより、金星熱圏と中間圏の上下結合に寄与する大気波動モードの同定とその運動量輸送を定量的に明らかにすることに初めて成功した先駆性の高いものである。得られた数値実験結果は、今後の中間圏-熱圏大気循環の地上観測や衛星ミッションの計画立案・策定にも寄与するものである。論文およびプレゼンテーションの内容は、背景となる物理の理解、結論および将来展開への提案等、水準に達するもので、著者が自立して研究活動を行うに必要な高度な研究能力と学識を有することを示している。以上の理由により、星野直哉提出の博士論文は、博士（理学）の学位論文として合格と認める。